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Modeling of Melt-Infiltrated SiC/SiC Composite Properties

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Summary

The elastic properties of a two-dimensional five-harness melt-infiltrated silicon carbide fiber reinforced silicon carbide matrix (MI SiC/SiC) ceramic matrix composite (CMC) were predicted using several methods. Methods used in this analysis are multiscale laminate analysis, micromechanics-based woven composite analysis, a hybrid woven composite analysis, and two- and three-dimensional finite element analyses. The elastic properties predicted are in good agreement with each other as well as with the available measured data. However, the various methods differ from each other in three key areas: (1) the fidelity provided, (2) the efforts required for input data preparation, and (3) the computational resources required. Results also indicate that efficient methods are also able to provide a reasonable estimate of local stress fields.

Introduction

Ceramic matrix composites (CMC) are attracting a lot of attention and are the subject of much research as potential candidate materials for high-temperature applications. Potential applications include hot-engine-section components (e.g., blades, vanes, combustion liners, and nozzles) as well as certain airframe structural components, particularly those in hypersonic applications and those at the point of impingement, such as wing leading edges, which see significant heating enhancement due to aerothermal issues. In addition, hot-engine-section components reach very high temperatures and require active cooling, thereby reducing the engine efficiency. Ceramics and high-temperature composites, particularly CMCs, are candidate materials to replace the high-density, lower temperature materials currently being used for those structural components.

Continuous-fiber-reinforced CMCs offer several advantages for both room- and high-temperature applications: high specific stiffness and strength, higher toughness and graceful failure than monolithic ceramics, environmental stability, and improved wear resistance. A weak fiber-matrix interface in CMCs allows the toughening mechanisms such as fiber bridging, crack deflection, matrix microcracking, fiber debonding, and fiber pullout to be combined to reduce residual stresses and eliminate catastrophic failures. However, current CMCs do not have a well established material property design database nor do they have validated and verified design and analysis methodologies so that the designers and analysts can use these materials reliably in critical aerospace structures. Demonstrated durability of this relatively new class of materials is a major challenge. Consequently, there is a need to develop verified and validated physics-based structural analysis tools that relate the new CMC woven and braided fiber architectures to property and durability constraints, enabling long-term exposure of CMCs to high temperatures for extended periods of time and varying (cyclic) stresses. Although efforts directed at the development of CMCs have primarily focused on improving the properties of the constituents as individual phases, it has become increasingly clear that for CMCs to be successfully employed in high-temperature applications, research and development effort should also focus on optimizing the synergistic performance of the constituent phases within the as-produced microstructure of the complex-shaped CMC part. Furthermore,

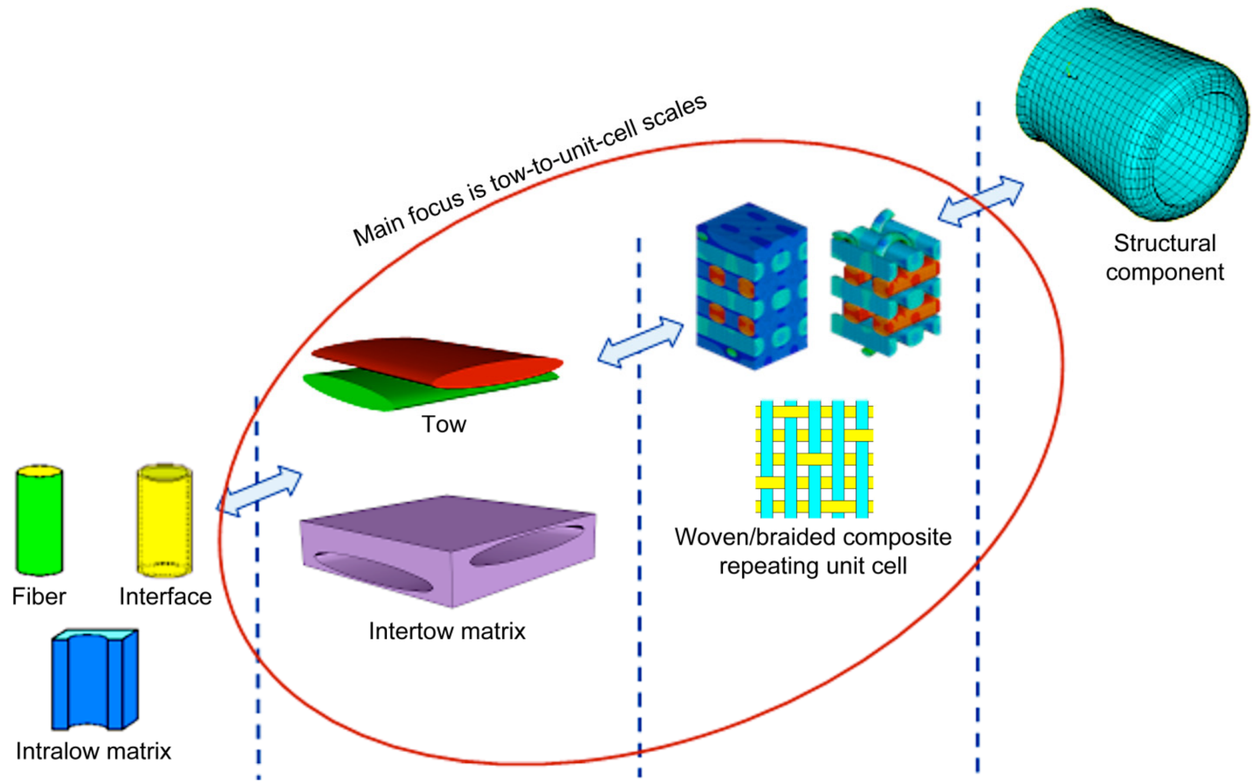


Figure 1.—Applicable scales in woven composite continuum modeling.

the design and analysis tools should enable selection and optimization of the key properties of interest within the physical and chemical constraints of the chosen CMC process. Most technically viable CMC methods have focused on a generic approach in that the fiber is assembled into a woven preform of the CMC part which is then infiltrated with desired interphase (coating) and matrix materials. These processes lead to complex microstructures with multiple constituents, which make their analysis challenging. Figure 1 shows applicable scales in woven-composite continuum modeling. Accurate prediction of elastic properties and deformation of these advanced composites is a very important step because it affects the prediction of scatter in design properties of a composite as well as its time-dependent behavior.

A range of methods (i.e., simple "rule of mixture," micromechanics-based approaches, a hybrid approach, and the finite element analysis method) are used to predict the thermal and/or mechanical properties of a model melt-infiltrated silicon carbide fiber/silicon carbide matrix composite (also known as N24A MI SiC/SiC) at two use-temperatures. The results from these analyses are compared with available measured data. Observations are made on the computational effort and computational time involved with each of the analysis methods.

Material Details and Constituent Properties

The N24A model material system used in this analysis is a MI SiC/SiC composite system with continuous length fiber tows of Sylramic[1]-iBN fiber woven into a five-harness woven fabric preform as shown in Figure 2. Two mutually orthogonal sets of yarn are interlaced with each other. Various types of weaves can be formed depending upon how the pattern in the interlaced region is repeated. In this case, a "warp," or longitudinal fiber tow, is interlaced with every fifth "fill," or width fiber tow, to create a five-

[1] COI Ceramics, Inc.

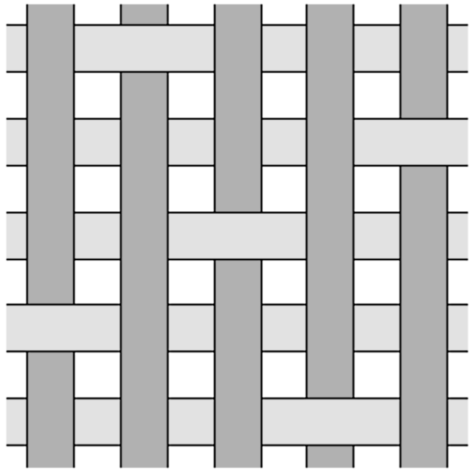


Figure 2.—Repeating unit cell of five-harness woven fabric preform.

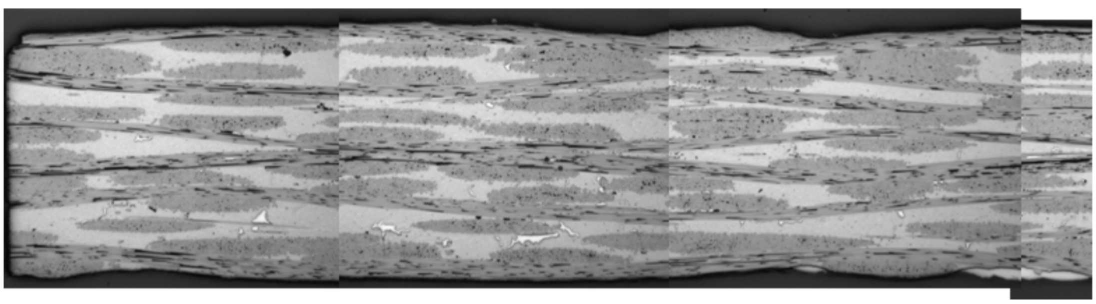


Figure 3.—Photomicrograph of N24A MI SiC/SiC composite.

harness satin-weave fiber architecture. In the straight sections of the fiber tow regions, construction is like a [0°/90°] (or cross-ply) laminate. There are wavy portions of the fiber tow, and there are matrix-rich areas. The volume fraction of the matrix-rich regions depend upon the weave geometry and can contribute a substantial fraction of the overall volume of the composite. Fiber tows or fiber yarns are usually composed of several hundreds or thousands of monofilaments. Fiber tow cross-section dimensions in the as-fabricated composites depend upon the weave geometry as well as the fiber type. Another important parameter is ends per inch (epi); that is, the number of fiber tows per linear inch of material. Given the epi and the ply height, the overall fiber volume fraction in the composite can be determined. The woven fabric is stacked in multiple layers or plies such that the consolidated N24A MI SiC/SiC composite is a five-harness weave, 20 epi, with a $[0°/90°]_{4s}$ layup.

Similarly, once the fiber preform is made, an interfacial coating is deposited on all fiber surfaces by a chemical vapor infiltration (CVI) process. In the case of the N24A system, a silicon-doped boron nitride (BN) coating is deposited around each fiber surface. The ratio of the coating thickness to the fiber diameter is around 6 percent. Usually, the volume fraction of the coating is determined from the weight gain of the fiber perform. The preform is then infiltrated by a CVI-SiC matrix, which usually fills the area within the tow (intratow) and then forms a very thin coating around the fiber tow. The preform is then almost fully densified by a slurry-casting melt infiltration process. Again, the volume fractions of different matrix phases are estimated by measured weight gains and knowing the densities of those phases. In the case of N24A material, overall fiber volume fraction is around 0.36. The composite has eight plies for a total thickness of 2 mm (0.08 in.), and each fiber tow has an as-fabricated elliptical shape with a total thickness of 0.125 mm (0.005 in.) and an aspect ratio of 9:1. A photomicrograph of N24A material is shown in Figure 3.

The constituent properties assumed at room temperature and a use-temperature of 1204 °C (2200 °F) are listed in Table I.

TABLE I.—N24A MI SiC/SiC CONSTITUENT MATERIAL PROPERTIES[a]

Property	iBN-Sylramic Fiber		CVI-BN		CVI-SiC		MI-SiC	
	RT	1204 °C	RT	1204 °C	RT	1204 °C	RT	1204 °C
Young's Modulus, GPa	380	365	21	14	380	358	310	276
Poisson's ratio	0.17	0.17	0.22	0.22	0.17	0.17	0.17	0.17
Density, g/cm^3	3.2	---	1.4	---	3.2	---	2.9	---
Coefficient of thermal expansion, 10^{-6}/K	4.6	8.0	5.2	10	4.6	9	4.7	9
Thermal conductivity, W/m·K	43	21	3.1	1	70	33	68	25

[a]CVI is chemical vapor infiltration, MI is melt infiltration, and RT is room temperature.

Analysis Approaches

Here brief descriptions of the various analytical approaches investigated for modeling the N24A elastic properties is provided.

Laminate Approximation

The properties of the N24A MI SiC/SiC composite were computed by treating it as a $[0°/90°]_s$ cross-ply laminate, using classical lamination theory. As shown in Figure 4, a multiscale approach was employed wherein the 0° and 90° plies were modeled locally using the Generalized Method of Cells (GMC) micromechanics theory (Ref. 1) with each ply containing a repeating unit cell consisting of an infiltrated tow and MI matrix. There are two local representations of the tow cross section: a rectangular and an elongated cross-shaped cross section as indicated in Figure 4. To calculate the effective properties of the woven composite using the multiscale laminate approximation, the effective properties of each ply are first determined from the tow and MI properties using GMC. These homogenized ply properties are then used within classical lamination theory to approximate the properties of the composite.

This multiscale laminate approximation captures most of the primary geometric characteristics of the woven composite microstructure; that is, the bi-directionality of the tows are accurately represented as is the presence of distinct regions of MI matrix. Thus, the CVI matrix present within the tows and the MI matrix do not need to be treated as one effective SiC matrix. In addition, the elongated nature of the tows is captured locally within the GMC unit cell representation. The main geometric attribute of the real five-harness satin (5HS) woven composite that is neglected in the multiscale laminate representation is the undulation of the tows, since the microstructure, which in reality is woven in the 5HS pattern, is represented as a [0°/90°] layup, with no crossover of the tows.

Micromechanics-Based Approaches

The two micromechanics approaches investigated to determine the N24A MI SiC/SiC elastic properties are described.

MAC/GMC

The Micromechanics Analysis Code with Generalized Method of Cells (MAC/GMC) is software released by NASA Glenn Research Center for micromechanics analysis of composite materials (Ref. 2). The software is based on a the method of cells family of micromechanics theories, including doubly and triply periodic versions of the GMC (Ref. 1) and the High-Fidelity Generalized Method of Cells (HFGMC) (Ref. 3). These theories employ doubly or triply periodic repeating unit cells to represent the composite microstructure. The unit cells consist of an arbitrary number of rectangular or parallelepiped

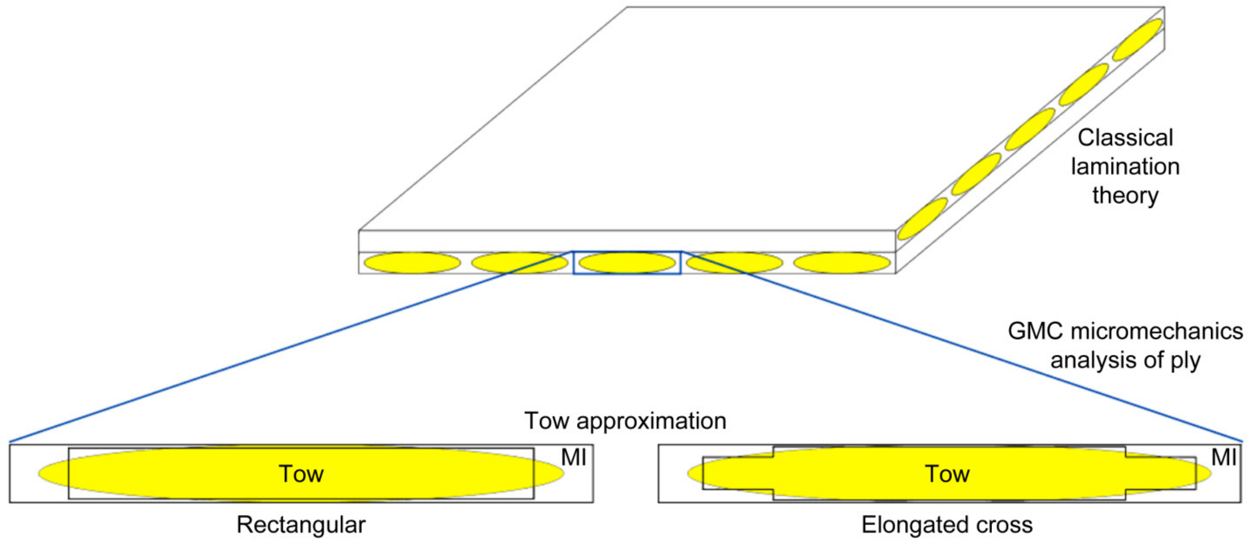


Figure 4.—Multiscale approach for laminate analysis; MI is melt infiltration, and GMC is Generalized Method of Cells.

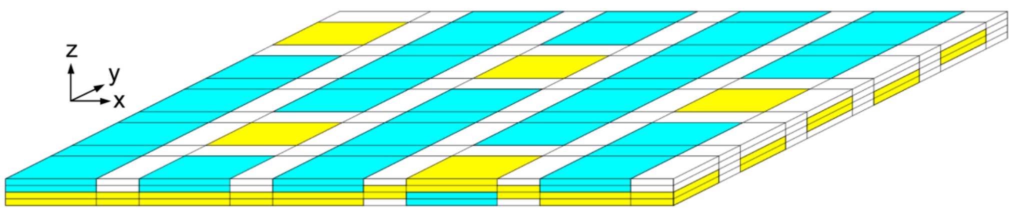


Figure 5.—High-Fidelity Generalized Method of Cells (HFGMC) triply periodic repeating unit cell employed to predict properties of N24A MI SiC/SiC composite.

subcells, each of which may contain a distinct material. The GMC and HFGMC homogenize the repeating unit cell to determine the effective properties of the composite material and also localize stresses and strains applied on the repeating unit cell to recover the local stresses and strains in the subcells. The ability to recover these local fields makes GMC and HFGMC ideal for implementation of local nonlinear theories that account for inelasticity, damage, and interfacial debonding on the scale of the constituent materials. The MAC/GMC software includes many such local theories and can also be called from within finite element analysis to enable the micromechanics theories to operate at the integration point level within a structural analysis.

The primary difference between GMC and HFGMC is the order of the displacement field assumed within the subcells in the respective formulations. In GMC a linear displacement field is assumed, whereas in HFGMC the displacement field is quadratic. The higher order displacement field employed in HFGMC provides the theory with greater accuracy, especially in terms of the constituent stress and strain fields, but this additional accuracy comes at a significant price in terms of computational efficiency.

Herein the doubly and triply periodic versions of HFGMC have been employed to predict the properties of the N24A MI SiC/SiC composite. The triply periodic repeating unit cell, consisting of 400 subcells, is shown in Figure 5, while the doubly periodic repeating unit cell, consisting of 656 subcells, is shown in Figure 6. In both cases, the effects of tow inclination in the crossover regions are captured by appropriately rotating the effective tow properties in the relevant subcells.

The triply periodic repeating unit cell accurately captures the bi-directionality of the tows, includes regions of pure MI matrix, and approximates the elongated cross section of the tows. Further, unlike the multiscale laminate approximation, the triply periodic HFGMC repeating unit cell captures the tow crossover regions according to the 5HS weave pattern.

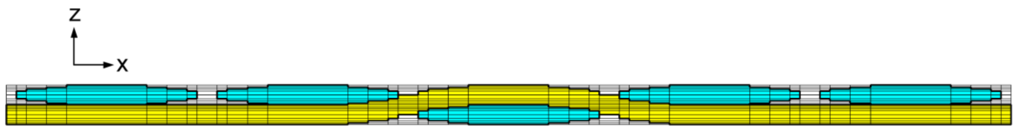


Figure 6.—High-Fidelity Generalized Method of Cells (HFGMC) doubly periodic repeating unit cell employed to predict properties of N24A MI SiC/SiC composite.

In contrast, the doubly periodic unit cell (Fig. 6), despite representing the crossover region more accurately than the triply periodic unit cell (because of a more refined subcell discretization), is constant in the y-direction. Therefore, the doubly periodic repeating unit cell considers only a single cross section of the actual three-dimensional repeating unit cell geometry. This cross section, as indicated by the red dotted line in Figure 5, is located in the middle of a tow oriented in the x-direction. Because this is the cross section within the three-dimensional geometry with the largest area fraction occupied by the x-direction tow, it would be expected that this model would overpredict the x-direction stiffness. Further, the represented geometry is incorrect in the y-direction, as the geometry is constant in this direction. Thus, properties other than those associated with the x-direction are highly suspect.

In the case of GMC, only the triply periodic version of the theory has been employed. The geometry of the repeating unit cell is identical to that used for the triply periodic version of HFGMC (Fig. 5). Previous work (Ref. 4) has indicated that standard GMC tends to underpredict the stiffness of woven composites (because of its less accurate first-order displacement field assumption). To overcome this shortcoming, a two-step homogenization procedure was developed (Ref. 4) wherein the repeating unit cell is first homogenized through the thickness (z-direction in Fig. 5) and then homogenized in the x,y-plane to arrive at the effective properties of the composite. This two-step method is similar to the procedure used in W–CEMCAN and pcGINA (discussed below) for modeling woven composites. Herein, both the standard one-step GMC method and the two-step method have been used.

W–CEMCAN

The W–CEMCAN (Woven Ceramic Matrix Composite Analyzer) is an outgrowth of the CEMCAN computer code (Ref. 5), which was developed for continuous-filament-reinforced laminated CMCs. It employs a novel fiber substructuring concept. The code was further enhanced to analyze composite materials consisting of stacked two-dimensional woven fabric with multiple constituents. Micromechanics approaches, in general, model all constituents—fiber, coating, and matrix materials—explicitly. Therefore, in this kind of approach, one can get a very detailed representation of stress fields in the constituent materials at a fraction of the computation time that is usually required for numerical methods such as finite element analysis. The approach used is quite general and generic and, in fact, can be applied to any type of satin-weave architecture.

The modeling approach will be explained very briefly here. For a detailed explanation, reader is referred to Reference 6. Figure 7 shows a cross section of the unit cell of a five-harness weave and a vertical slice taken from the cross section showing details of different constituents. In the regions where the fiber tow is straight, the construction is like a [0°/90°] cross ply. In the undulated part of the fiber tow, fiber is assumed to follow a certain geometrical path. The tow shape and sizes are assumed that match closely with what is observed in the photomicrographs. For each slice, classical lamination theory is applied to obtain homogenized properties of the slice. Proper rotations and the judicious selection of the fiber tow angles is made as the inclination of the fiber tow is in x,z-plane (as opposed to the usual x,y-plane). Lamination theory is applied again to homogenize the properties of the slices to obtain homogenized properties of the unit cell. The process is equally applicable to an N-harness [0°/90°] composite construction as well. The user inputs a number of slices used for the unit cell as well as the tow geometry, constituent volume fractions, and constituent material properties. Since this technique is an analytical technique based on composite micromechanics equations, it is computationally much more efficient than a fully numerical analysis technique such as finite element analysis. Any level of detail can

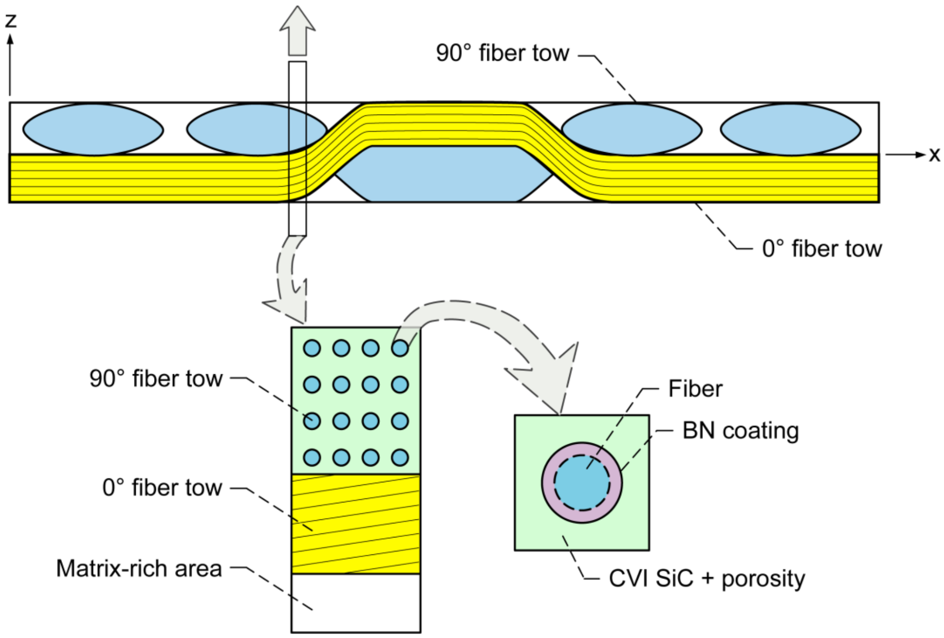


Figure 7.—W–CEMCAN five-harness weave analysis.

be modeled. The incorporation of processing, effects of voids in the constituents, and environmental degradation can be incorporated in the analysis as well.

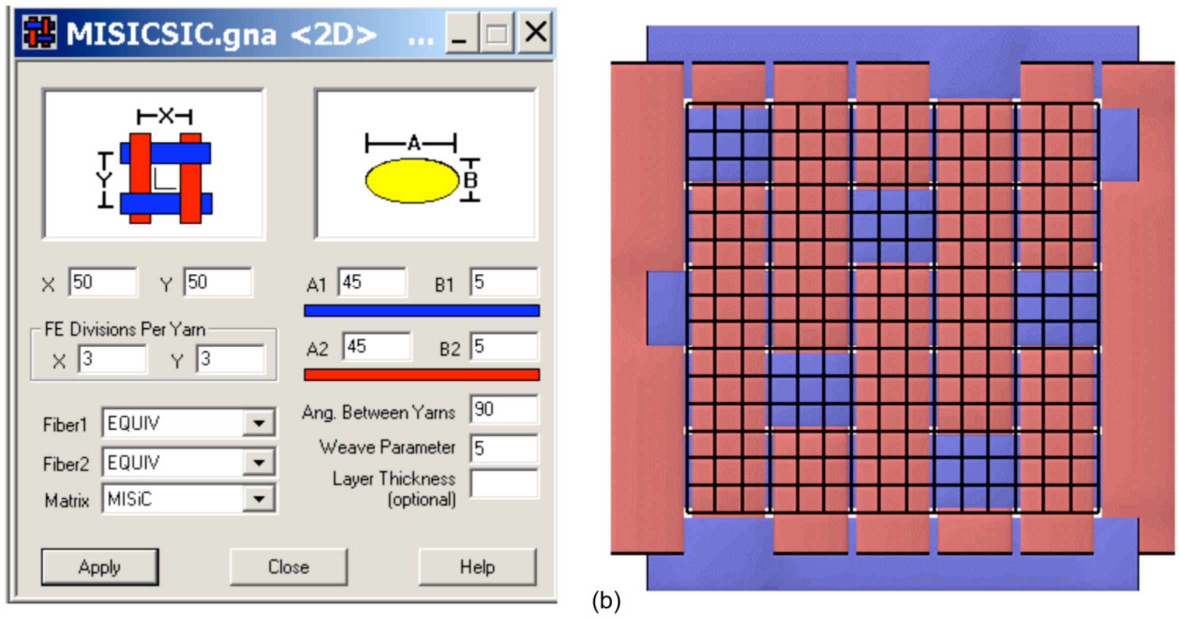
pcGINA (Hybrid Approach)

The modeling approach in pcGINA (Graphical Integrated Numerical Analysis) (Ref. 7) combines the homogenization techniques typically used in micromechanics-based approaches and traditional three-dimensional finite element analyses. Homogenization approaches based on laminate theory could become difficult to extend for composites with complex architectures. The use of traditional finite element analysis could be limited by the complexity of preform architecture, meshing problems, and need for a large number of elements. In turn, that would mean that a large amount of computational time will be needed just to obtain a set of thermal and mechanical properties. Complex three-dimensional preforms would require hundreds of thousands of elements, making it computationally intensive.

The pcGINA computer code combines the two approaches as a hybrid finite element approach. The repeating unit cell (RUC) of the fiber preform is identified and divided into a coarse mesh of hexahedral brick elements with fiber and matrix around each integration point. Material homogenization is carried out around each integration point using analytical equations to define the anisotropic material response. Assumptions of repeatability and continuity of the unit cell are used. Standard finite element method techniques are used to calculate the elastic properties of unit cell. The reader is referred to Reference 7 for a detailed description of this methodology. The pcGINA code provides a variety of architectures that can be modeled and a very user-friendly interface, as shown in Figure 8.

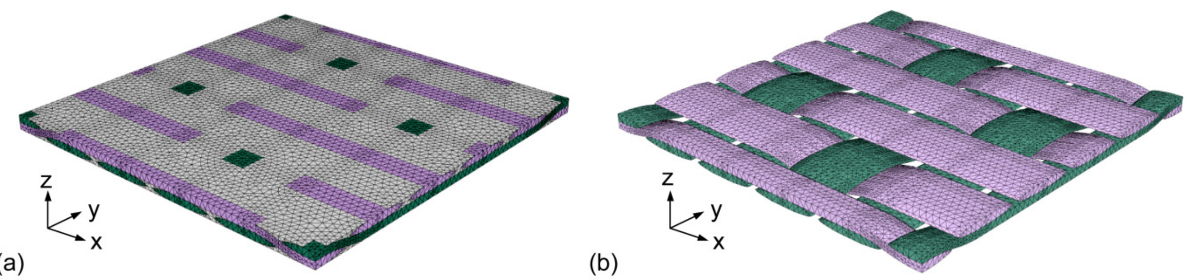
Finite Element Analysis (Fully Numerical)

In the finite element unit cell approach, the woven composite repeating unit cell is explicitly modeled and meshed with appropriate boundary conditions. The ABAQUS (Ref. 8, Dassault Systèmes) general-purpose finite element software was used for this purpose. As in the other methods, effective tow properties and MI matrix properties were used to define the materials in the composite repeating unit cell. Both two- and three-dimensional finite element models were constructed. The full three-dimensional model is shown in Figure 9, both with and without the MI matrix elements included. By employing



(a) (b)

Figure 8.—pcGINA five-harness woven composite analysis. (a) Screen shot of user interface. (b) Repeating unit cell geometry.



(a) (b)

Figure 9.—Three-dimensional ABAQUS (Dassault Systèmes) finite element mesh of N24A MI SiC/SiC composite. (a) With melt-infiltrated (MI) matrix elements included. (b) Without MI matrix elements.

172 406 C3D10 elements, the geometry of the weave is captured quite accurately, as shown. However, the tows are only one element thick in most locations. Note that the tows were inclined appropriately using orientations within the model.

A two-dimensional generalized plane strain finite element mesh for the woven composite is shown in Figure 10. As was the case with the doubly periodic HFGMC, a plane model such as this can only represent one particular cross section of the truly three-dimensional unit cell geometry. The model is therefore expected to be overly stiff in the x-direction, and properties associated with other directions are suspect. Also, because all multi-axial properties cannot be extracted from a plane model, a three-dimensional model of the two-dimensional geometry was constructed, as shown in Figure 11. This model, consisting of 3208 CPEG3 and CPEG4R elements, was used to predict the elastic properties of the composite. When possible, results were compared with those predicted by the generalized plane strain model shown in Figure 10, and in all cases, these results were nearly identical. As in the three-dimensional model, the tows were inclined in the crossover regions via use of orientations within the appropriate elements.

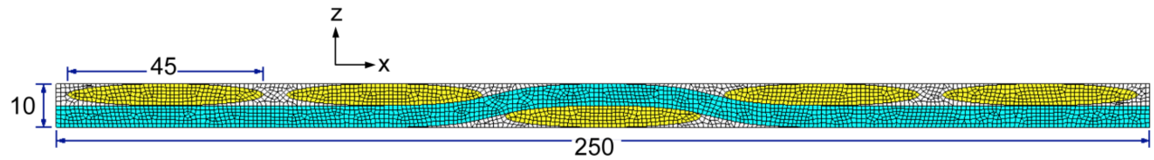


Figure 10.—Two-dimensional generalized plane strain finite element mesh of N24A MI SiC/SiC woven composite. Dimensions are in milli-inches (mil); 1 in. = 1000 mil.

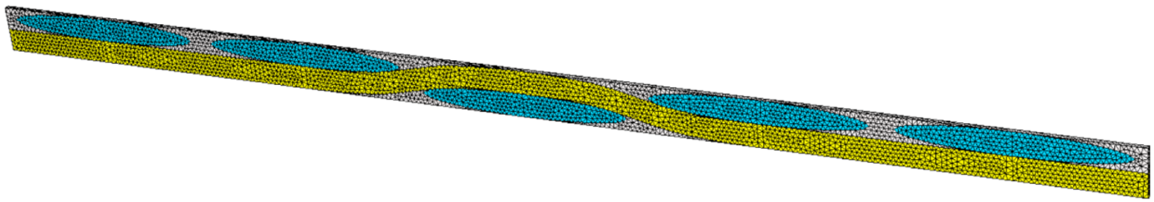


Figure 11.—Three-dimensional finite element mesh used to extract multi-axial material properties.

Results and Discussion

The constituent properties of N24A MI SiC/SiC material used here are shown in Table I. The constituent properties are shown at two use-temperatures: room temperature and 1204 °C (2200 °F). Effective tow properties (i.e., a tow consisting of Sylramic-iBN fiber, BN coating, and CVI-SiC matrix), computed by treating the tow as a unidirectional composite at two use-temperatures, are shown in Table II. The various methods outlined above were exercised, and the overall predicted homogenized composite properties at two use-temperatures are shown in Tables III and IV. Surprisingly, all the methods employed provide very consistent and reasonable values of elastic properties as shown by the results: properties computed by various techniques differ from each other by less than 10 percent. Comparisons with the available measured properties, also shown in Tables III and IV, are very reasonable except for the through-thickness modulus, which is typically overpredicted by at least a factor of 2 compared with the average measured value out of plane. The reason for this discrepancy is still under investigation; some of the proposed possibilities being considered are (1) debonding of fiber tows at top and bottom and (2) significant amount of preferential shape and direction of cracks and/or porosity. Presence of preferential shape and direction of cracks and/or porosity reduce the through-thickness modulus. In addition, partial or complete debonding of fibers also reduces the composite modulus. However, the existence of these features needs to be verified in actual composite micrographs. Nonetheless, the currently predicted effective property results (see Tables III and IV) are excellent—particularly in the case of high-temperature CMCs—considering that the constituent materials have in situ effects associated with their properties as well as significant variability present in the measured properties.

TABLE II.—EFFECTIVE TOW PROPERTIES WITHIN N24A MI SiC/SiC COMPOSITE COMPUTED FROM MICROMECHANICS

Property[a]	Room temperature	1204 °C
Young’s Modulus, E_1, GPa	320	306
Young’s Modulus, E_2, GPa	149	120
Poisson’s ratio, ν_{12}	0.176	0.175
Poisson’s ratio, ν_{23}	0.150	0.137
Shear modulus, G_{12}, GPa	59.6	47.6
Coefficient of thermal expansion, α_1, 10^{-6}/°C	4.6	8.5
Coefficient of thermal expansion, α_2, 10^{-6}/°C	4.7	8.8
Thermal conductivity, κ_1, W/m·K	45.4	21.6
Thermal conductivity, κ_2, (W/m·K)	22.1	9.0

[a]1 indicates longitudinal fiber direction.

TABLE III.—HOMOGENIZED N24A MI SiC/SiC COMPOSITE PROPERTIES AT ROOM TEMPERATURE

Property[a]	Analysis method[b]										Experiment (average)
	Multiscale laminate theory		W–CEMCAN	GMC (3D)		HFGMC		pcGINA	Finite element analysis		
	Rectangular tow	Cross-shaped tow		One-step	Two-step	2D	3D		2D	3D	
Young's modulus,											
E_x, GPa	250	253	266	233	252	253	247	248	253.7	251.9	252
E_y, GPa	250	253	266	233	252	234	247	248	233.6	251.9	252
E_z, GPa	183	180	178	183	183	163	183	174	163.3	180.2	~82
Poisson's ratio, ν_{xy}	0.13	0.129	0.12	0.125	0.127	0.126	0.121	0.12	0.139	0.129	0.13
Shear modulus, G_{xy}, GPa	74.1	76.4	78	70.7	74.5	67.6	71.4	102	72.6	76.5	---
Execution time, s	0.015	0.015	<1	0.08	---	0.22	2.9	~4	60[c]	2640[c]	---

[a]Refer to Figure 9 for axis directions.
[b]GMC and HFGMC are generalized method of cells and high-fidelity GMC, respectively; 2D and 3D are two-dimensional and three-dimensional, respectively.
[c]Involves four cases.

TABLE IV.—HOMOGENIZED N24A MI SiC/SiC COMPOSITE PROPERTIES AT 1204 °C

Property[a]	Analysis method[a]										Experiment (average)
	Multiscale laminate theory		W–CEMCAN	GMC (3D)		HFGMC		pcGINA	Finite element analysis		
	Rectangular tow	Cross-shaped tow		One-step	Two-step	2D	3D		2D	3D	
Young's modulus,											
E_x, GPa	224	227	243	203	225	230	220	221	230.5	225.9	230
E_y, GPa	224	227	243	203	225	209	220	221	208.7	225.9	230
E_z, GPa	151	149	148	151	151	132	151	141	132.4	159.5	---
Poisson's ratio, ν_{xy}	0.12	0.12	0.11	0.11	0.12	0.12	0.12	0.11	0.13	0.12	---
Shear modulus, G_{xy}, GPa	60.9	63.4	64	57.3	60.9	54.9	58.0	86	59.4	63.7	---
Thermal conductivity, κ_x, W/m·K	17.3	17.6	19	15.3	16.3	16.4	16.9	18	15.5	15.8	20
Thermal conductivity, κ_z, W/m·K	12	12.6	12	11.6	11.7	10.1	11.9	12	9.6	9.8	18
Coefficient of thermal expansion, α_x, 10^{-6}/°C	8.7	8.7	8.6	8.7	8.7	8.8	8.8	7.8	8.6	8.7	6
Execution time, s	0.015	0.015	<1	0.08	---	0.22	2.9	~4	60[b]	2640[b]	---

[a]Refer to Figure 9 for axis directions.
[a]GMC and HFGMC are generalized method of cells and high-fidelity generalized GMC, respectively; 2D and 3D are two-dimensional and three-dimensional, respectively.
[b]Involves four cases.

Even though the various methods showed little difference in predicting the homogenized elastic properties of the composite, these methods vary broadly based on their fidelity, capabilities, input manipulation, and the computational expense needed to acquire this full set of elastic properties. All the methods examined are similar in the sense that they all first identify a woven composite repeating unit cell (RUC); however, each method had a different range of fidelity and utility (see Table V). It is worth noting that the properties predicted here are for a nominal five-harness architecture where no geometrical imperfections such as ply misalignment and nesting have been considered. Execution times for computing

TABLE V.—FIDELITY AND COMPUTATIONAL EXPENSE FOR VARIOUS ANALYSIS METHODS

Analysis method	Relative fidelity	Relative expense
W–CEMCAN	Moderate	Low
pcGINA	Moderate	Low/moderate
Generalized method of cells (GMC)	Moderate	Low
High-fidelity GMC (HFGMC)	Moderate/high	Moderate
Two-dimensional finite element analysis	Moderate/high	High
Multiscale laminate approximation	Moderate	Low
Three-dimensional finite element analysis	Very high	Very high

elastic properties by different methods are also shown in Tables III and IV. Computational times for all methods are very small except for the two- and three-dimensional finite element analyses, which demand orders of magnitude increases in execution times. This is as expected, since in general, finite element analyses require significantly more computational resources. Note, these RUC calculations provide the material properties at a given point in a structure, but if one wanted to predict the response of a structure composed of this composite material, such calculations would likely have to be repeated thousands of times, thus rendering numerical analysis methods quite intractable. Additionally, analytical (e.g., micromechanics-based) methods can provide stresses at various levels of scale quite efficiently (e.g., at the fiber, coating, and intratow matrix scale) while the high-fidelity computationally intensive methods, like finite element analysis, are limited to providing stress at the tow and MI matrix level only unless one employs computationally intensive local global analyses. Hence, fiber debonding from the coating within a tow cannot conveniently be modeled using finite element methods. For this reason, it is widely believed that numerical analysis techniques such as finite element methods should be used at the structural (component) scales, while analytical methods should be used at the mesoscale and microscale for obvious practical reasons (Fig. 1), even though numerical methods are often used at the microscale to verify the analytical or hybrid approaches.

Finally, it should be noted that local fields (e.g., tow and matrix fields) are dependent upon the specific analysis approach being pursued. This is illustrated in Figure 12 where an in-plane strain of 0.1 percent was applied to the different models discussed herein, and the computed von Mises stress field is shown. As expected, higher fidelity and thus highly computationally intensive models provided greater detail (accuracy) in local stress fields and may possibly capture stress concentrations at a point. For example, maximum von Mises stress in the matrix varies according to the method employed. The one-step GMC predicted a value of 246 MPa, multiscale laminate analyses predicted a value of 280 MPa, and the two- and three-dimensional HFGMC predicted values of 313 and 294 MPa, respectively. Two- and three-dimensional finite element analyses predicted maximum von Mises stress in the matrix as 321 and 327 MPa, respectively. Some of these numbers are dependent on the level of detail and discretization employed. However, as can be seen from these results, the significantly more-efficient methods still give very reasonable estimation of local stress fields.

In light of these local field results, the question becomes whether or not extremely accurate local fields must be provided in order to enable accurate predictions of component life. The answer is more dependent upon one’s modeling philosophy because of the fact that in actuality both driving force (applied loads and local architecture) and material resistance (dependent upon both local architecture and processing methodology) are spatially varying throughout a given component or even in a given test specimen (see Fig. 13). Therefore, one can assume a fixed (pristine) architecture with specific architectural parameters that can be varied (e.g., tow spacing, tow shape, etc.) to obtain a statistical distribution of resulting stresses. These stresses then can be compared with statically and spatially varying material strength values. Alternatively, one can analyze local architecture (e.g., ply shifting, ply rotation, nesting, etc.) and the flaw and porosity distribution in great detail using high-fidelity numerical analyses to obtain detailed local stresses (i.e., driving forces). These stresses can be compared with a fixed value of material strength. Both of these approaches can potentially give similar results, but the former approach is

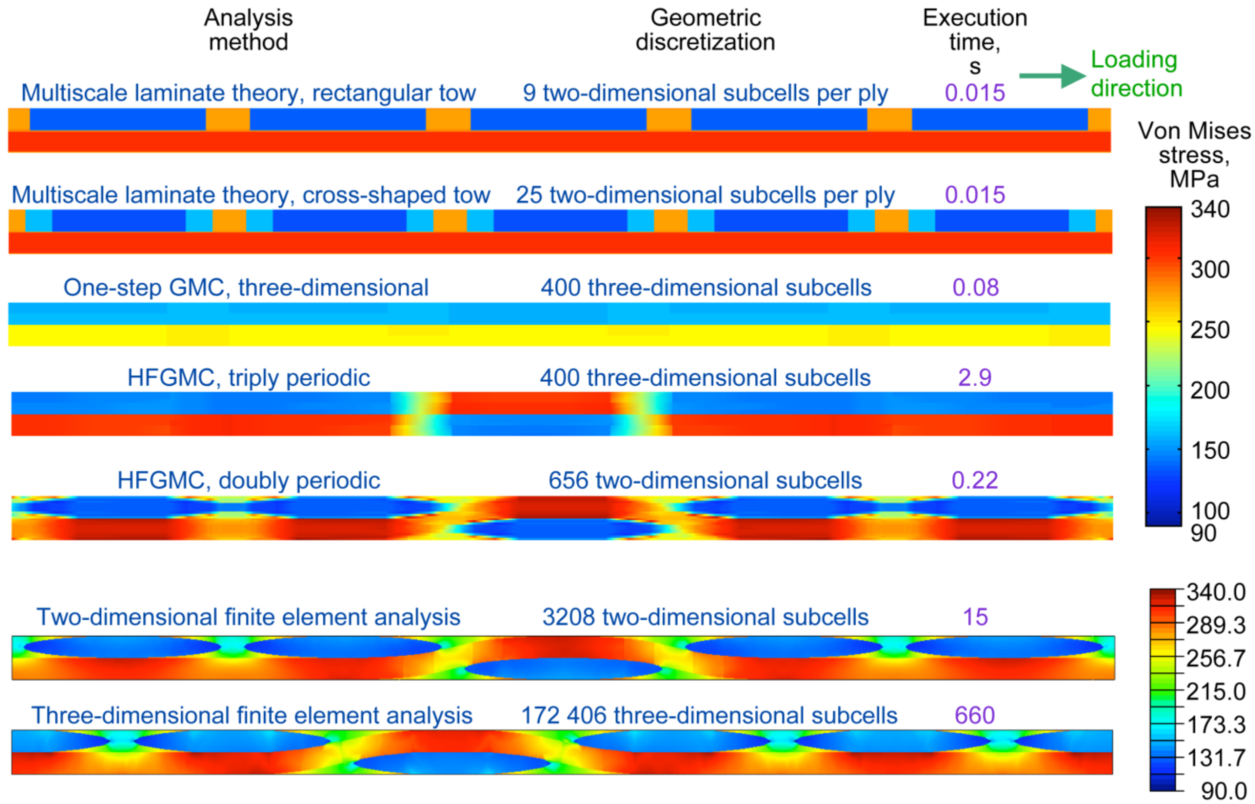


Figure 12.—Von Mises stress at 1204 °C and at applied in-plane strain of 0.1 percent calculated with various analysis methods. GMC is Generalized Method of Cells, and HFGMC is High-Fidelity GMC.

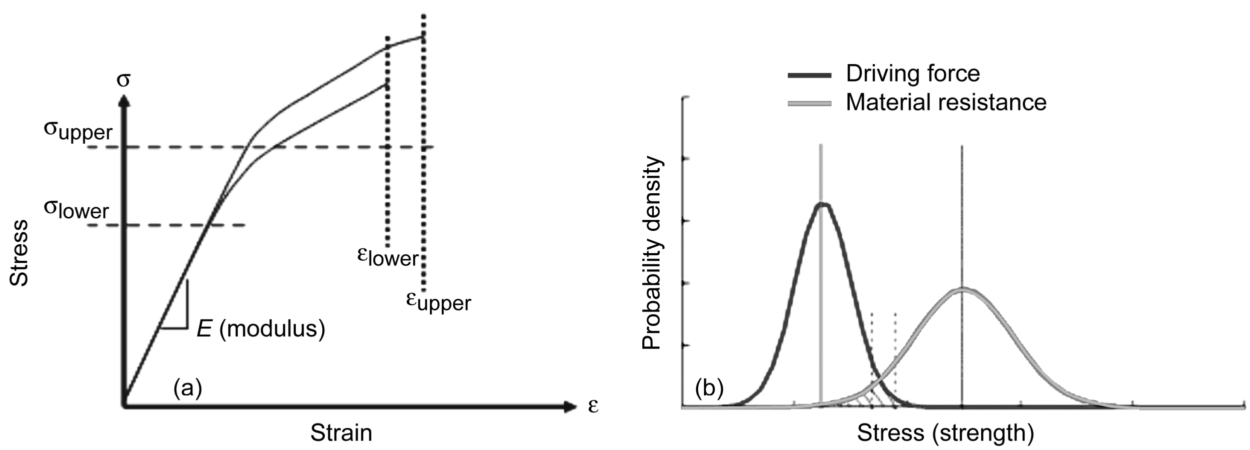


Figure 13.—Life prediction rationale. (a) Stress versus strain. (b) Probability density versus stress (driving force and resistance are both functions of architecture, processing, etc.).

much more computationally efficient. However, in reality both stresses and strengths show statistical and spatial variation because of variability in primary architectural and manufacturing parameters, which are not mutually exclusive. The structural analyses that involve high-fidelity numerical analyses at a given point can easily become intractable. Bednarcyk et al. (Ref. 9) illustrated this in terms of predicting creep deformation response. Consequently, adopting a computationally efficient methodology (e.g., analytical) will enable one to span multiple scales in a composite structure more efficiently to enable not only computation of component life but also design of the specific material as well. A demonstration of the difference between these two modeling approaches with respect to life prediction will be reserved for future work.

Concluding Remarks

Several approaches that include laminate analysis method, woven composite micromechanics analysis (W–CEMCAN), and (MAC/GMC), hybrid analysis (pcGINA), and two- and three-dimensional finite element analysis methods were used to compute the elastic properties of a five-harness satin-weave melt-infiltrated SiC/SiC high-temperature ceramic matrix composite. All of these approaches do a reasonably good job of predicting the elastic properties of the composite. Properties compare reasonably well with the available test data, and properties computed by different methods are within 10 percent of each other. However, substantial differences exist in fidelity provided and computational effort needed by the various methods. Numerical analysis methods require considerably more computational effort than analytical methods. Results also indicate that efficient (semi-analytical) methods are able to provide very good approximations of local stress fields.

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14. ABSTRACT
The elastic properties of a two-dimensional five-harness melt-infiltrated silicon carbide fiber reinforced silicon carbide matrix (MI SiC/SiC) ceramic matrix composite (CMC) were predicted using several methods. Methods used in this analysis are multiscale laminate analysis, micromechanics-based woven composite analysis, a hybrid woven composite analysis, and two- and three-dimensional finite element analyses. The elastic properties predicted are in good agreement with each other as well as with the available measured data. However, the various methods differ from each other in three key areas: (1) the fidelity provided, (2) the efforts required for input data preparation, and (3) the computational resources required. Results also indicate that efficient methods are also able to provide a reasonable estimate of local stress fields.

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